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A REVIEW OF WELDING PROCESSES FOR HY-100 SUBMARINE HULL COMPONENTS

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ABSTRACT

A review of possible welding processes for production welding of HY-100 steels in naval vessels, particularly submarine pressure hulls, is presented. These processes include: SAW, SMAW, GMAW, GTAW, and FCAW. In addition, this report investigates recent developments in welding processes, including narrow gap and synergic pulsed GMAW, that could be used for production welding of naval vessels.

The objectives of the report include: evaluating the suitability and productivity of the various processes, speculating on the potential problems likely to be encountered, and outlining the known welding procedures. The sources of consumables for HY-100 steels, both commercially available and experimental, are discussed.

A review of proposed research at CANMET in this subject area is also presented.

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UNE REVUE DES PROCÉDÉS POUR LES COQUES DE SOUS-MARIN DES ACIERS HY-100

par

N.J. Smith

RÉSUMÉ

Ce rapport examine les procédés pouvant être utilisés pour souder les aciers HY-100 lors de la constructuion des structures navales, particulièrement les coques de sous-marin. Les procédés retenus sont les suivants: soudage sous flux (SAW), soudage manuel avec electrode enrobée (MMA), soudage sous gaz avec fil fusible (GMAW), soudage sous gaz avec électrode en tungstène (GTAW), et soudage avec électrode fourrée (FCAW). De plus, on y discutera des récentes innovations apportées au soudage avec faible écartement des bords, au soudage synergique sous gaz avec fil fusible (GMAW), susceptibles de profiter à la construction de structures navales.

Ce rapport vise à évaluer l'utiliter et la productivité des méthodes de soudage; résumer leurs modes opératoires tout en soulignant les difficultés qui peuvent être encourues; identifier les fournisseurs de matériel tel le métal d'apport HY-100, les flux et les gaz protecteurs.

Finalement, les plans de recherche dans ces domaines à CANMET sont présentés.

INTRODUCTION

The welding design and inspection requirements of United States (and presumably Canadian) HY-100 components for combat submarine structures is specified by MIL-STD-1688(SH), 'Fabrication, Welding, and Inspection of HY-80/100 Submarine Applications'. These components are divided into three categories: the pressure hull structure, the containment structure, and the non-pressure hull structure. The most stringent design and inspection requirements are for the pressure hull structure, and this paper will focus on some problems associated with the welding of the pressure hull.

HY-100 steel is a quenched and tempered high strength C-Mn-Ni duplex bainitic/martensitic steel. A typical composition is shown in Appendix 2, (Table 1, page 5). For military applications it is produced to MIL-S-16216J(SH) 'Steel Plate, Alloy, Structural, High Yield Strength (HY-80 and HY-100)' with a specified minimum yield strength of 689 MPa (100 ksi). The specified Charpy impact requirements for HY-100 plate (13 mm and 50 mm thick) are 75 J at -18°C and 41 J at -84°C.

The welding consumable qualification specification for HY-100 is MIL-STD-23765/2C (SH). This qualification specification requires Charpy V-notch, Dynamic Tear, and tensile testing of the weld metal. In addition, explosion bulge tests have to be satisfied. Canadian emphasis is expected to be on the explosion bulge test for both process and consumable qualification. The target values specified in this MIL-STD for the weld metal are shown in Table 1. For comparison purposes, the target values for HY-80 weld metal are also shown. The transverse Charpy V-notch requirements for the weld metal are 81 J at -18°C and 47 J at -51°C. These requirements differ slightly from those specified for the base plate. The Charpy specimens are located in the weld metal so that the upper face of the specimen is 3 mm below the top surface of the base plate and the notch is located at the centerline of the weld.

In addition to the specified mechanical properties, welds in submarine hulls must also possess adequate corrosion properties. The corrosion properties of the weld metal are usually governed by the specified composition of the welding consumables, although consideration of the corrosion properties might indicate the need for a final layer of a more corrosion resistant material to cover the weld metal. However, a discussion of corrosion properties is outside the scope of this paper.

Good welding practice for HY-100 steels has been reviewed in two papers, Shackleton (1), and Flax, Keith, and Randall (2). These reviews present much useful data and adequately cover much of the work carried out before 1972. Bird (3) presents a later review of welding processes for high-strength steels in naval applications. The expected problems can be summarized from these review papers.

Welding procedure defects, such as lack of fusion, porosity, and slag inclusions, can be corrected by proper procedure development or judicious selection of the welding process. The relative merits of the various welding processes with respect to the propensity for procedural defects are described below.

Metallurgical defects are more difficult to avoid. The metallurgical problems associated with HY-100 welds are generally:

1. A brittle martensitic layer is formed in the heat-affected zone of the base plate. The presence of this brittle layer limits the overall toughness of the weldment, especially in CTOD tests, as discussed by Nakanishi, Komizo & Fukuda (4). This is a problem associated with the base metal but the selection of a welding process does have some effect since the thermal efficiency of the process, and the resulting net heat input, determines the size of the brittle layer.
2. Liquation cracking in the heat-affected zone of the base metal occurs as micro-cracking or fissuring between the grain-boundaries adjacent to the fusion line. An example is shown in Appendix 2 (Figure 6, p. 13). This type of cracking can reduce the notch toughness of the heat-affected zone, as discussed by McGrath and others (5) for HY-80 steels. It is caused during welding when inclusions melt (at about 1400°C), penetrating and weakening the prior austenite grain boundaries. Liquation micro-cracking can be avoided by changing the chemistry of the base plate so that the Mn/S ratio is increased, primarily by reducing the sulfur content to very low levels (about 0.004%), and partly by increasing the manganese content to the maximum allowable, similar to the discussion of HY-80 steels by McGrath and others (5). However, if the base plate is likely to incur liquation micro-cracking during welding because of a relatively low Mn/S ratio, then the incidence of cracking can be reduced to some degree by reducing the heat input. This might also affect the selection of a welding process.
3. Hydrogen-assisted cracking can occur in both the weld metal and the heat-affected zone. The primary concern for multipass HY-100 welds, like those used for the welding of submarine pressure hulls, appears to be transverse weld-metal cracking. An example is shown in Appendix 2 (Fig. 5, p. 13). This is likely due to the combination of longitudinal residual stress and the tensile strength of the weld metal. Methods of avoiding hydrogen-assisted cracking by immediate post-weld heat treatment are discussed below.
4. Solidification cracking, especially in the root pass of the weld, is also a problem because of the segregation of nickel during solidification (Machado Ref 6). One method of avoiding this problem is to limit the nickel content of the welding consumable to less than 2%. In addition, a welding procedure which requires the back-gouging of the first pass would avoid much of the problem. Other procedures, such as the use of a lower strength electrode for the first pass, are discussed below.

WELDING PROCESSES

Only a few welding processes are suitable for shipyard welding of hull components, and the selection of processes for combat submarine applications of HY-100 steels is further restricted by the availability of consumables capable of meeting the strength and toughness requirements specified in MIL-STD-23765/2C (SH). The processes that can be used are not necessarily operated with maximum economy because of the heat input and interpass temperature limitations specified for the welding of HY-100 steels in MIL-STD-1688(SH). In this specification, the maximum heat input is limited to 2.2 MJ/m and the maximum interpass temperature specified is 150°C.

The processes considered in this paper for welding HY-100 submarine hulls are shielded metal arc welding (SMAW), gas metal arc welding (GMAW), gas tungsten arc welding (GTAW), flux-cored arc welding (FCAW), and submerged arc welding (SAW).

For out-of-position welding of HY-100 to HY-100 steel in the pressure hull, the only approved process is SMAW using basic, low hydrogen electrodes. This is a versatile and highly adaptable process and all the other processes considered for submarine hull construction must be compared to SMAW. However, it is dependent on operator skill and it is not very productive compared with most other processes. High quality, high deposition rate processes are limited to joints of simple geometry, usually in the flat position.

Processes with inherently high heat inputs, such as electrogas and electroslag welding, are not used because of the poor mechanical properties of the weld. High power density processes, such as plasma arc, electron beam, and laser welding, are not used for submarine hulls, but could be considered for welding small components, which are later placed in the hull structure. These processes usually have close fit-up requirements, which are not considered practical in a shipyard environment.

SUBMERGED ARC WELDING

Submerged arc welding (SAW) is routinely used in the fabrication of naval ships. It is currently used in the U.S. for welding 50 mm to 100 mm thick HY-100 aircraft carrier decks and other HY-100 components. The welds are high quality and exhibit good mechanical properties. Automation makes the welds easily reproducible.

Although submerged arc welding is limited to the flat position only, it is easily adaptable for welding pressure hulls. It can be used for welding both the longitudinal and circumferential joints in the hull sections and for welding the ribs inside the hull by rotating the work piece under the welding head.

In the U.K., for example, HY-80 submarine pressure hull units have been joined using SAW (3). A double-vee joint preparation is used. The root run is made using SMAW. The outer

portion of the joint is then filled using SAW, with Oerlikon OES3 wire and OP41TT flux, with a heat input of 2.2 MJ/m. The root is then backgouged, and the inside portion of the joint is filled using SMAW, Fig. 1.

SAW requires special approval by NAVSEA before it can be used for welding HY-80 and 100 components. This is probably to ensure that the wire/flux combinations are matched with respect to alloying and residual elements. The MIL-STD specifies a 'neutral flux' in the sense that no alloying additions are deliberately added to the flux. The best toughness is obtained with a highly basic flux, which lowers the oxygen content of the weld metal. The basicity of the flux is not necessarily a direct measure of the oxygen content, but there is a general trend that increased basicity reduces weld metal oxygen levels (7,8). The yield strength is a balance between cooling time and alloying level, and some alloying elements, particularly carbon, are transferred from the flux to the weld metal. The amount transferred appears to vary with current (9,10). For a given flux, there is probably an optimum choice of welding current and voltage to achieve the best combination of yield strength and notch toughness.

Currently, only the Linde and Lincoln 120S-1 wires are approved by NAVSEA. Two fluxes, Oerlikon OP121TT and Lincoln 880M, are approved. Thyssen and Kobe will be submitting wires and fluxes to NAVSEA. In addition, Alloy Rods has submitted a metal cored wire, 120S-1, for approval by NAVSEA.

Current practice in the U.S. for thicker section HY-100 components, such as aircraft carrier decks, is to use lower strength HY-80 consumables (11,12). This results in a slight undermatching of the yield strength, but improved notch toughness.

Preliminary work at CANMET was done to develop and evaluate welding procedures for SAW of HY-100 steels with approved HY-100 consumables, Linde 120S-1 wire (2.4 mm diam) and OP121TT flux, using a double-V joint preparation to simulate production joints. A copy of the preliminary report is included in Appendix 2. The preheat temperature was 93°C and the interpass temperature was limited to 150°C maximum. Three heat inputs: 2, 3, and 4 MJ/m, were used. The welds from all three heat inputs had transverse hydrogen-assisted cracking in the weld metal (Fig. 5, p. 10,11,12, Appendix 2). The amount of cracking appeared to decrease with increasing heat input, probably because of the increased time for hydrogen evolution. However, liquation micro-cracking in the heat-affected zone was seen at the highest heat input, 4 MJ/m (Fig. 5, p.12, Appendix 2).

A second series of welds was made using the same conditions. Immediately after welding, each welded plate was flame cut transversely into two sections. One section from each weld was placed in a furnace before it cooled and was soaked for 2 h at 260°C. No hydrogen-assisted cracking was found in the sections that had been placed in the furnace. The Charpy V-notch and tensile results from the weld sections placed in the furnace exceeded the target values. The results of the Charpy tests are shown in Fig. 2.

One concern with SAW is avoiding hydrogen-assisted cracks caused by moisture in the flux. The fluxes used for welding HY-100 are usually of high basicity and are therefore either bonded or agglomerated. They absorb moisture readily. Both Thyssen, as stated by Grosse-Wordemann & Dittrich (9), and Oerlikon (Mike Hayes, Houston, Telephone interview) recommend that for HY welding applications the flux be carefully baked before use, instead of using it directly from the manufacturers containers. The baking temperature should be 300 to 400°C, which is higher than the 260°C recommended by the MIL-STD.

The method of recycling the flux after welding also requires special study, since the fluxes absorb moisture so readily. The procedure adopted by a shipyard will depend on the individual practice of the shipyard and the humidity conditions. United Kingdom practice for lower strength steels is to recirculate the flux, adding 25% new flux each time and baking the flux after each work day as suggested by Bird (3). However, Bird recommends not recycling the flux for HY-80 steels, and therefore, presumably, HY-100 steels.

Future work at CANMET will investigate the effect of changes in the welding variables, especially current and voltage. Franke (10) conducted a series of bead-on-plate welds at a constant heat input of 2.2 MJ/m, varying the current between 400 and 600 amps, and the voltage between 33 and 37 V. One wire/flux combination was used. It was found that both the chemical composition and the microstructure of the weld metal changed with current. As the current was increased, the manganese content decreased and the chromium and copper levels increased. Changes in voltage had a similar but less marked effect. Franke reported that the maximum amount of what he identified as acicular ferrite was obtained at both the lowest current and the lowest voltage. It would appear that while deposition rates and productivity favor high current, notch toughness considerations favor low current and voltage. Further investigation is required, however. Lau (7) found that the nitrogen content decreased as the current increased, although Franke found no change. Generally, a high nitrogen content is associated with lower notch toughness. In addition, Deb, Challenger, and Therrien (13) concluded that the toughest microstructure for HY-100 is not acicular ferrite, as for carbon-manganese steels, but a fine, autotempered martensite which is obtained with fast cooling times. It may not follow that the proportion of this martensite is dependent on welding parameters but is determined solely by the cooling time.

Additional in-house work at CANMET will investigate increasing the deposition rate by using the SA tandem-arc process, at the same maximum total heat input of 2.2 MJ/m. Grosse-Wordemann and Dittrich (9) and Bird (3), have published some results on tandem-arc trial welds. Grosse-Wordemann and Dittrich reported a deposition rate of 13 kg/h, which compares favorably with a single wire deposition rate of about 9 kg/h. The yield strength exceeded the specifications, but the notch toughness levels were marginal. The Charpy V-notch impact values met the target

values, but without the comfortable margin that would be required for shipyard production. Some development work is need to improve the notch toughness.

SHIELDED METAL ARC WELDING

Shielded metal arc welding (SMAW) is the only process qualified by NAVSEA for all positions in submarine hulls. As far as is known, only two manufacturers, Alloy Rods and Lincoln, have qualified electrodes (12018M2) at the present time. Other manufacturers have electrodes that meet the mechanical properties, including Teledyne-Mackay and Trimark.

Future developments in SMAW include improving the coatings so that there are fewer inclusions in the weld metal, which should improve the notch toughness. The coatings will also be improved so that less moisture is picked up during exposure to the atmosphere. This has been done with new welding electrodes for lower strength steels. It will likely mean that more potassium and lithium will be used to replace some of the sodium now present in the coatings (3,14). A double coating technique has also been employed by some manufacturers to reduce hydrogen levels. The latest version of the military specification for SMAW electrodes, MIL-0022200/10A (SH), limits the initial moisture levels in the coatings to a maximum of 0.10% and also limits the moisture pickup so that after 9 h exposure at 80% relative humidity and 27°C the moisture content is a maximum of 0.20%. In addition, the diffusible hydrogen level for welds deposited with electrodes removed from the sealed manufacturers container is also limited to a maximum average value of 3.2 mL/100 g for electrodes 3.2 mm or smaller diameter and 3.5 mL/100 g for electrodes 4.0 mm or larger diameter. The purpose of this clause is to limit the initial diffusible hydrogen content of the weld metal and reduce the risk of hydrogen-assisted cracking.

Good welding practice for SMAW is discussed by Shackleton (1) and will not be discussed in detail here. Briefly, good practice includes stringer beads to reduce the heat input and a short arc to reduce porosity and nitrogen pick-up. Thin beads allow more time for hydrogen diffusion and reduce the risk of hydrogen-assisted cracking. Delong (15) recommends a time delay between passes of 1 h minimum to allow time for hydrogen diffusion. Although this is not specifically recommended by the MIL-STD, because it reduces productivity, it should be considered if hydrogen-assisted cracking is a recurring problem.

A weaving pattern for vertical welding increases the heat input, and this may be of some concern. Shackleton (1) reviews procedures for vertical welding, including suggested weaving patterns. However, as far as is known, for HY-100 no comprehensive study has been completed on the effects of vertical welding on heat input. It is difficult to quantify because the results are largely dependent on operator technique.

GAS METAL ARC WELDING

Conventional gas metal arc welding (GMAW) can produce welds with low hydrogen content and excellent mechanical properties, but it has only limited application in submarine fabrication because of the metal transfer characteristics, which make the process prone to fusion defects. Spray transfer needs a high current density, which is difficult to control. It has occasionally been used to weld stiffeners on the hull (3). Short circuit (or dip) transfer is prone to inter-run and sidewall fusion defects and it must be used with a carbon dioxide shielding gas for a stable arc. The resulting notch toughness is too low for combat ships.

One variation, which is approved by NAVSEA to the MIL STD, is a patented process called TIME gas, which uses a four gas mixture, argon-helium-carbon dioxide-oxygen, to achieve axial small droplet transfer, similar to spray transfer, at lower current thresholds (Ref: J. Church, Weld Process International Ltd, Mississauga, ON).

Pulsed GMAW is another variation that achieves spray transfer at low average current, which makes it feasible to use for manual welding, including out-of-position welding. It has not been adopted by fabricators to any great extent because of the complexity in choosing the appropriate parameters. Synergic pulsed GMAW is a recent development that matches average current with the wire feed speed and simplifies the parameter selection. However, there is still some discussion on the fundamental relationships governing synergic pulsed GMAW. A useful discussion of automatic pulsed GMAW for Arctic vessel applications is presented by Dorling and others (16). Other development work on pulsed synergic GMA welding of HY steels has been carried out at the Welding Institute of Canada (17). However, development work is still required, especially for manual out-of-position welding. Ontario Hydro has extensive experience in pulsed GMAW for nuclear and pressure vessel applications, and has concluded that the main problem of manual pulsed GMAW is lack of penetration and lack of fusion (M. Tinkler, private communication). In automatic pulsed GMAW, this problem is overcome, to some extent, by precise placement of each weld bead (with a tolerance of, say, 0.3 mm) but this level of precision is not likely to be achieved by a welder during manual welding.

The synergic pulsed GMA process is currently used in the U.K. for welding HY-80 submarine hulls, using an AWP 450 series power source, manufactured by GEC. A double-vee groove is welded, using a split weave technique to get the required penetration, and argon- 2% oxygen shielding gas. A glass rod backing is used for the root run, which eliminates the need for back-gouging (3).

The efficiency and therefore the actual heat input of pulsed GMAW are unknown. Studies of conventional GMAW by Franke (10) have shown that the cooling time of conventional GMAW is twice as fast as comparable SAW, indicating that the thermal efficiency of GMAW is about one-half that of SAW. The efficiency of pulsed GMAW would likely be even less, resulting in an even faster cooling time. This would allow a split weave technique, but the width of the

resulting heat-affected zone is apparently twice as large, according to Bird (3). This may be of some concern for toughness considerations and should be investigated. The preheat temperature specified in the MIL STD for GMAW is the same as SAW and SMAW. Shackleton (1) states that, because of the faster cooling times for GMAW, a higher preheat should be used to avoid hydrogen-assisted cracking, especially for the root pass. However, notch toughness considerations indicate that a faster cooling time is more desirable for achieving a tougher microstructure in the weld metal, and a higher preheat would slow the cooling time. The relationship between cooling time and notch toughness is discussed in further detail below.

Two narrow-gap GMAW processes, a Kobe twist wire system and an NKK rotating arc system, are being studied under a CANMET contract at the University of Alberta, by B. Patchett (Contract No: D.S.S. No. 37ST-23440-6-9142). Narrow-gap welding produces welds with superior mechanical properties and less distortion. A rule of thumb suggests that narrow gap welding is only economical in thicknesses of over 100 mm, because of the extra machining and fit-up costs. However, it was pointed out earlier in the discussion that welding processes for HY-100 are rarely operated at their full economic potentials. Since the cost of HY-100 weld metal is so high, and since it is relatively difficult to achieve the target mechanical properties, it might be practical to use a narrow-gap process for welding HY-100 plates thinner than 100 mm.

A feature of narrow-gap welding is the faster cooling time. Nominally lower strength filler metals, such as for HY-80, can be used. This was done by Laing, Heid, and Pollack (11), who investigated GMAW-NG of 50 mm thick HY-100 plate using 100S-1 wire (which is an HY-80 wire), and nominal heat inputs from 1.9 to 2.8 MJ/m. The resulting yield strength was slightly low, but the ultimate tensile strength and the notch toughness values were easily exceeded. The deposition rate was reported to be about 6 kg/h.

GAS TUNGSTEN ARC WELDING

The gas tungsten arc welding process (GTAW) gives the cleanest weld metal deposits and the highest notch toughness. It can also be used for very low heat inputs, avoiding distortion and limiting both the size of the brittle layer and the amount of liquation micro-cracking in the heat-affected zone. However, the adoption of GTAW has been limited by low deposition rates, 1 to 2 kg/h (1). To increase the deposition rates, a GTAW hot wire process was developed. In this process, the wire is preheated by an external alternating current so that it is just below the melting point before entering the weld pool. A deposition rate of 6 kg/h was reported by Flax, Keith, and Randall (2) in a program to study the hot-wire welding of HY-130 steel. This is competitive with other processes. Hot-wire GTAW requires more elaborate and expensive machinery and is limited to flat position welding only but it is easily automated.

GTAW has not been used extensively in shipyards but it is commonly used in the aerospace industry, especially for critical components. It is also used by some Japanese fabricators to weld HY110 and HY130 steel structures, and it is probably the only process suitable at the present time for steels structures with strengths above 750 MPa (18).

Buried autogenous GTAW of steel for naval applications is a recent development that has been studied by Lukens (19). Lukens reports that butt welds in a thick section A710 high strength low alloy steel (HSLA 80) was successfully welded using buried autogenous GTAW process. The process eliminates the need for plate edge preparation, reduces the number of weld passes, and does not require filler metal. Lukens feels that this process could be competitive with submerged-arc welding for high strength steels. The process can also be used for web-to-flange fillet welds. However, as far as is known, the process has not yet been used for welding of HY-100 steels.

FLUX CORED ARC WELDING

Flux-cored arc welding (FCAW) is a potential process for submarine hulls. It is a continuous wire process, using tubular electrodes, with high deposition rates. It is not prone to fusion defects because of the method of metal transfer, unlike GMAW. However, it is not approved by NAVSEA for the welding of HY-100 to HY-100 steel, because the weld metal notch toughness is usually too low at present. The use of FCAW for the welding of lower strength steels to HY type steels is discussed by Ferree (30).

Flux-cored electrodes are generally made from a mild steel tube containing alloying elements and slag forming elements within the core. They are generally classified in two types, according to the slag type: acid core and basic core. Acid core wires contain rutile or titanium dioxide. These wires form a fast freezing slag, and have low spatter. They are suitable for out-of-position welding, but the notch toughness is usually too low for military applications. Basic core wires contain calcium carbonate or fluorspar. The resulting welds have good strength and notch toughness properties, but the wires are currently restricted to producing welds in the flat position only because the slag is too slow in freezing.

Several consumable manufacturers, including Alloy Rods, Teledyne Mackay, Corex (Trimark), and ESAB, are actively developing tubular wires for HY-80 and HY-100 steels. The first three companies have submitted tubular wires to the U.S. Navy for approval.

According to Ferree (20), the most common flux cored wire for welding HY-80 and HSLA 80 steels is MIL-101TM. A MIL-71T-1-HYC wire is designed to weld ordinary carbon steels and HTS steels to HY-80, A710 (HSLA 80), and HY-100 steels. Ferree (20) also recommends that flux cored electrodes be properly stored and conditioned (or baked) before use. Some electrodes are less prone to moisture pick-up than others, but it is difficult to determine the

susceptibility of an individual wire. Therefore, a conservative approach is to adopt Ferree's recommendations.

WELDING CONSUMABLES

COMPOSITION

Wires approved by NAVSEA for GMAW, GTAW, and SAW for HY-100 are designated 120S-1, and approved electrodes for SMAW are designated 12018M-2. The compositions of approved electrodes are specified in the MIL standard. At present, there is a limited number of approved consumables available. One reason for the difficulty in producing qualified electrodes is the diverging targets that a consumable must meet: yield strength, corrosion resistance, and notch toughness. Higher alloying levels usually increase the yield strength and the corrosion resistance, but decrease the notch toughness and electrode usability, in terms of bead profile and arc stability.

Recent work by Grosse-Wordemann & Dittrich (9) and Machado (6) has suggested that the compositions should be modified. In particular, the nickel content should be less than 2% to prevent solidification cracking. In addition, for higher notch toughness, there should be no chromium in the weld metal. This is also suggested by the work of Hart (21). However, some chromium may be required for corrosion resistance and the MIL-STD specifies 0.6% Cr maximum.

AVAILABILITY OF CONSUMABLES

The welding consumable industry has undergone a number of ownership and trade name changes recently, but some of the major manufacturers who are known to be active in developing consumables for HY-100 include: LTEC, formerly known as Linde, who also market KOBE wires and fluxes in Canada, LINCOLN, who bought the Airco consumable line in Canada, HOBART, who market Oerlikon in Canada, and who also own Trimark and Corex, CANADIAN LIQUID AIR, who market Alloy Rod in Canada; ESAB, who own Murex and Philips; THYSSEN; and TELEDYNE-MCKAY. A list of companies and contacts is included in Appendix 1.

ALTERNATIVE PROCEDURES

The need for new welding consumables and procedures for HY-100 was outlined in a report by the U.S. National Research Council (22). This report indicated the most effective use of weld metal strength, and recommended the use of lower strength consumables to weld HY type steels. Lower strength electrodes and wires are easier to make and use. This would also have the advantage of reducing the preheat required to avoid hydrogen-assisted cracking in the weld metal,

reducing welding costs. The recommendations in this report were based partly on some Japanese work on the effect of lower strength filler metal in weld joints, including fatigue and notch toughness properties. The Japanese work, which is referenced in the report, focussed on HT-80 steel, a Japanese grade with an ultimate tensile strength of 80 kg/mm, or 713 MPa. The yield strength is about 689 MPa, therefore the steel is nearly equivalent to HY-100.

One Japanese procedure for welding HT-80, discussed in the U.S. NRC Report (22) utilizes a lower strength electrode for the root pass. This has the advantage of reducing root pass cracking due to both hydrogen-assisted cracking and solidification cracking and it also improves the notch toughness, especially in CTOD or Dynamic Tear tests, which emphasize the root region. Since the root pass is usually backgouged, the overall strength of the joint is not affected significantly but even if the root pass is not backgouged, the strength and fatigue properties are not adversely affected by having a small portion of the welded joint made from a lower strength metal, as shown by some Japanese work cited in the U.S. NRC Report (22). Another Japanese procedure for welding HT-80 steel, also discussed in the U.S. NRC Report (22) uses a lower strength electrode at the corners of the weld beads, almost as a 'temper bead', Fig. 3. The purpose of these beads is to prevent cracks from initiating in the brittle layer of the heat-affected zone.

A similar approach was proposed in a recent article by Ritter and Dixon (23), who related recent Australian experience with the welding of HY-80 steels for submarine applications. They reported that a variation of the temper bead approach, which they called a 'top hat bead', increased the notch toughness. This 'top hat bead', a small bead placed in the corners of the weld metal, was similar to the Japanese procedure shown in Fig. 3. This bead also prevented a crack from initiating in the brittle portion of the heat-affected zone. However, unlike the Japanese procedure, the small bead had the same yield strength as the rest of the weld deposit, but it projected beyond the joint preparation about 8 mm. A schematic of this 'top hat bead' is shown in Fig. 4. After the top hat bead is placed, the top passes are then deposited, and the adjacent passes temper the top hat bead. This weld performed well in the explosion bulge test.

Ritter and Dixon (23) also concluded that a weld made with a commercial grade E11018 electrode performed better in the explosion bulge test than an approved E11018M electrode because the yield strength of the E11018 electrode more nearly matched the base plate.

One difficulty with obtaining HY-100 welding wires is the long procurement time, often up to one year or more (Palermo, 24) because of the limited number of suppliers and the relatively limited market for these wires. Enough orders must accumulate to warrant a heat of the special alloy steel. The composition of the welding wire does not match the base plate exactly, since more manganese is required for oxygen control and less nickel is supplied to prevent solidification cracking. Tubular wires, both flux cored and metallic cored, may be a possible alternative to conventional solid wires. These wires have a shorter procurement time than solid wires, they are easier to make, they do not require large heats of special alloy, and they are usually

cheaper than equivalent solid wires. Metallic cored wires contain iron powder, deoxidisers, denitriders, and alloying elements within the core. They tend to be cheaper than solid wires of the same strength level, with a potentially shorter procurement time. Because they do not contain a flux, a separate shielding mechanism is required. They can be used either with gas shielding in the GMAW process, or with flux shielding in the SAW process. In GMAW, Ferree (20) reports that metallic cored wires give a more stable arc and a better bead profile than the equivalent strength solid wire. However, the weld metal usually has low notch toughness because of a high oxygen content resulting from entrapped air in the powder core. Further development of these wires is required.

COMPARISON OF WELDING PROCESSES

WELD METAL MICROSTRUCTURE AND TOUGHNESS

In general, the microstructure of the weld metal, therefore the tensile strength and the toughness, is governed by the cooling time from 800 to 500°C [T(8-5)]. Therefore, the cooling time of HY-100 weld metal must be carefully controlled to obtain the optimum combination of strength and notch toughness. Consideration of the cooling time will affect the choice of welding process. This is demonstrated in a study by Deb, Challenger, and Therrien (13), who compared the notch toughness of multi-pass SAW and conventional GMAW of 25 mm thick HY-100 plate. The two processes were compared by using identical welding wire (Linde 120), the same nominal heat input, 2.2 MJ/m, and almost identical welding parameters. For GMAW, the current was 400 amps, and the arc voltage was 28 V. For SAW, the current was also 400 amps, but the arc voltage was 35 V and the travel speed was adjusted to suit the heat input.

The cooling time [T(8-5)] for each weld was measured and a significant difference was found, even though the nominal heat input was the same. The cooling time of the GMA weld metal was 40% shorter than the cooling time of the SA weld metal. The microstructures of the weld metal resulting from the two processes were characterized using electron microscopy (TEM) and found to be significantly different, as well.

The microstructure of the gas-metal-arc weld metal consisted of a mixture of fine low carbon lath martensite, autotempered martensite, mixed bainites called B-II and B-III by the authors, and some twinned martensite. The "average packet width" of the weld metal microstructure was found by the authors to be 1.0 μ.

On the other hand, the microstructure of the submerged arc weld metal consisted of a mixture of coarse upper bainite, B-II bainite, and a distribution of carbides and cementite precipitates in a highly dislocated ferrite. The "average packet width" of this weld metal was found to be 2.6 μ.

It was concluded by Deb, Challenger, and Therrien that the faster cooling time [T(8-5)] of the GMA weld metal resulted in a smaller "average packet width".

The weld metal mechanical properties from both welding processes exceeded the target values specified in the consumable qualification code, MIL-E-23765/2C (SH), but the GMA welds were tougher since the ductile-to-brittle transition temperature (DBTT) for the GMA welds was reported to be -70°C, and for SA welds it was reported to be -20°C. The SA weld metal did have a higher upper shelf energy at +20°C.

Deb, Challenger, and Therrien (13) also concluded that the higher notch toughness of the GMA weld metal could be attributed to the smaller "average packet width". A similar effect between packet size and notch toughness was found by Kotilainen (25) in a study of a bainitic low alloy Cr-Mo steel, and by Naylor and Krahe (26), who studied the effect of bainitic packet size on notch toughness, and concluded that as the cooling time [T(8-5)] decreased, the packet size decreased, and the notch toughness properties increased.

These results would appear to indicate that a shorter cooling time [T(8-5)] is desirable for producing weld metal with good notch toughness. Therefore, if higher deposition rates are required, the consequent longer cooling times [T(8-5)] will result in weld metal of lower notch toughness. However, adequate notch toughness might be achieved by obtaining a higher proportion of acicular ferrite in the weld metal.

Acicular ferrite is also known as a tough constituent, because of a fine grain size (0.5 to 5 μm), a favorable dislocation density, and an absence of twin formation, as noted by Hoekstra, Munnig Schmidt-van der Burg and der Ouden (27). It differs from the bainitic microstructures discussed above because acicular ferrite grains are nucleated intragranularly, and usually require a slower cooling time.

Deb, Challenger, and Therrien (13) concluded that the low carbon lath martensite found in the GMAW weld-metal microstructure was a desirable component because it was tougher than comparable acicular ferrite. The notch toughness of low carbon lath martensite was also noted in recent research at CANMET on the notch toughness of weld heat-affected zones in HSLA-80 steels (J. Bowker, private communication). However, Deb, Challenger, and Therrien did not conclusively demonstrate the better notch toughness of this component compared to acicular ferrite, since they used a lower strength, low alloyed steel for comparison. More research is required in this area.

HYDROGEN-ASSISTED CRACKING

Another consideration in the selection of welding processes is the avoidance of hydrogen-assisted cracking, as mentioned previously. The hydrogen contents of the various processes vary with the quality of the consumables but it would be expected that GTAW and

GMAW have the lowest hydrogen content and that the flux shielded processes, SAW and SMAW, have the highest hydrogen content [see, for example, Graville (28) or Houldcroft (8)].

Even with the best processes, exceptional care and quality control are needed. Flax, Keith and Randall (2) and Bird (3) both review some aspects of quality assurance required to avoid hydrogen-assisted cracking. For HY-100 steels used for combat submarine applications, the rules of clean base metal and consumables, including dry gases and fluxes, must be meticulously followed. Welding wire, for instance, should be returned to proper storage facilities when not being used. Attention must be focussed on the handling of SAW fluxes and on SMAW stick electrodes to avoid moisture pickup before welding. Also, both flux cored and metallic cored wires should be properly stored and conditioned (or baked) before use, as discussed by Ferree (20).

In addition, the moisture content of the welding consumables, particularly SAW flux and SMAW electrode coatings, must be reduced to very low levels by the manufacturer. For instance, as mentioned previously, the latest version of the military specification for SMAW electrodes, MIL-0022200/10A (SH), limits the initial moisture levels in the coatings to a maximum of 0.10%.

HEAT-AFFECTED ZONE HYDROGEN-ASSISTED CRACKING

Because HY-100 has a high hardenability and transforms to a hard, untempered martensitic microstructure it is susceptible to hydrogen-assisted cracking in the heat-affected zone. This can be predicted by the Carbon Equivalent Number, given by Graville [(28), page 121] as:

$$C.E.N = C + (Mn + Si)/6 + (Ni + Cu)/15 + (Cr + Mo + V)/5$$

Using this formula, the Carbon Equivalent Number for the range of allowable composition for HY-100 steel is between 0.62 and 1.04. Any C.E.N. over 0.40 is considered high and indicates precautions such as preheat are necessary to avoid hydrogen-assisted cracking in the heat-affected zone.

WELD-METAL HYDROGEN-ASSISTED CRACKING

It has been suggested by Grosse-Wordemann & Dittrich (9), however, that for HY-100 steels hydrogen-assisted cracking is more likely to occur in the weld metal than in the heat-affected zone, especially in multi-pass groove welds, due to the increased hydrogen content in the weld metal and the high residual stresses present. The experience at CANMET would also seem to confirm this. This is opposite to the experience of welding HY-80, where cracking in the heat-affected zone is 'the most severe welding problem', according to Flax, Keith, and Randall (2). This trend is confirmed by Okuda et al (29), who concluded that the propensity for cracking in the

weld metal is related to the tensile strength of the weld metal deposit. This is also discussed by Matsuda, Nakagawa, and Shinozaki (18) and Shackleton (1).

INSPECTION AND TESTING

Weld metal cracking in multi-pass groove welds usually occurs just below the last layer of passes. According to Takahashi and Iwai (30), this is the location of maximum residual tensile stress and hydrogen concentration, since hydrogen diffuses along both temperature and stress gradients. The selection of inspection methods for quality assurance in production welds should be based on an awareness of this type of weld metal cracking. These hydrogen-assisted cracks are difficult to detect because of their tight, convoluted morphology.

In addition, quality assurance programs should include weldability tests to assess the propensity for cracking, using consumables that are conditioned similar to those used in actual production. One test that investigates transverse cracking in weld metal is the GBOP test, as discussed by Hart (21). Graville (31) reviews weld metal hydrogen-assisted cracking and also comments on weldability tests that should be used to investigate weld-metal cracking. Most of the weldability tests discussed in the literature investigate heat-affected zone cracking and not weld-metal cracking.

In addition, for lower strength steels, the hardness of the deposit is usually considered a good indication of susceptibility to hydrogen-assisted cracking. However, Hart (21) showed that this is not the case for HY-100 weld metal. Hart studied the effect of microstructure and hardness on hydrogen-assisted cracking in C-Mn-Ni deposits of 700 MPa yield strength, similar to HY-100. It was reported that for relatively high diffusible hydrogen contents, around 10 mL/100 g, the resistance to cracking was controlled by the weld metal hardness, as for lower strength steels. As the hardness increased from 200HV to 330HV the amount of cracking increased. However, at lower levels of diffusible hydrogen, less than 5 mL/100 g, which would be typical for the low hydrogen processes used for HY-100, the resistance to cracking was controlled by the microstructure and was relatively independent of the hardness. Hart found that a microstructure with good notch toughness, such as acicular ferrite, had less cracking than microstructural types such as ferrite with aligned MAC (martensite-austenite-carbide constituents). This would suggest that an arbitrary hardness value should not be a specification requirement for avoiding hydrogen-assisted cracking in high-strength steels.

POST-WELD HYDROGEN REMOVAL

Hydrogen-assisted cracking can be avoided by allowing enough time above about 100°C for hydrogen to diffuse out, reducing the hydrogen content below the critical concentration for cracking. This can be done by raising the preheat temperature or the heat input (or both) and thus increase the cooling time of the weld metal down to 100°C. This can be seen to some extent in

the results obtained at CANMET, shown in Appendix 2. As the heat input was increased from 2 MJ/m (Appendix 2, Fig. 5, p. 10) to 4 MJ/m (Appendix 2, Fig. 5, p. 12), the cracking became less severe. However, a slower cooling time from 800 to 500°C [T(8-5)] has a detrimental effect on both notch toughness and the amount of liquation micro-cracking, as discussed above.

Another method is to use an immediate low temperature post-weld heat treatment (hydrogen removal), by placing the welded component in a furnace or by retaining the heat sources used for the preheat for an extended period of time after the weld is completed. Since this is a relatively low temperature heat treatment, it does not affect the microstructure. Takahashi and Iwai (30) concluded that weld metal hydrogen-assisted cracking in thick-section pressure vessels could be reduced or eliminated by an immediate low temperature post-weld heat treatment. It remains to be determined what the optimum post-weld time and temperature are for hydrogen removal, although some guidance is offered by Takahashi and Iwai and by the David Taylor Naval Ship Research and Development Center (DTNSRDC), as discussed by Howden (22).

A post-weld hydrogen removal treatment is recommended. DTNSRDC (12) suggests such a treatment is not necessary, since it is felt that consumables and processes are available that have sufficiently low hydrogen content, but standard practice for submarine construction in shipyards is apparently to retain the electric resistance heaters on the weldment for up to 8 h for HY-100 steels (32,33).

DISCUSSION OF WELDING COSTS

It has been reported that the cost of welding is at least 20% (24), and can be up to 50% (13) of the total cost of naval ships. Thus, a saving in welding costs can cause a substantial reduction in the overall cost of submarine construction. These costs can be reduced by using welding processes with higher deposition rates, such as SAW and narrow-gap GMAW. Table 2 summarizes the deposition rates of the various processes discussed in this paper. Howden (22) discusses the relative cost of welding processes for HY-80 steels. The relative cost of deposited weld metal, including labor and materials, was calculated assuming a labor cost of $15/h. Briefly, the report concluded that for flat position welding the cost of weld metal deposited with manual stick electrode was $10/h, with a solid wire process (probably GMAW) it was $6/h, and for automatic SAW, it was $5/h.

However, other factors besides deposition rate, such as fit-up, preheat, and post-weld heating for hydrogen removal also affect the total cost of the process. These costs are difficult to quantify since individual shipyard practice varies. However, a general statement can be made that the automatic processes have more stringent fit-up requirements, and that the narrow gap processes would have the highest fit-up costs. The manual processes, in particular SMAW, are more tolerant of poor fit-up. Another consideration is the cost of hydrogen removal (either post-weld hydrogen

removal or conditioning the consumables). This cost is higher for the flux shielded processes (SAW, SMAW), especially SAW, since the flux is usually hygroscopic.

The overall cost of a welding process also depends on the incidence of defects that need repairing. The cost of repairing defects can be illustrated by the recent history of the first Trident submarine, the U.S.S. OHIO (34). The launching of that submarine was delayed almost two years, partly because of welding defects. When fabrication was nearly complete, all the accessible welds were re-examined. Almost one-third of those welds were found to contain defects which needed repairing. The cost of repairs was U.S. $2.6 million in 1981.

CONCLUDING REMARKS

Any welding process that is adopted for shipyard use must produce welds under qualification conditions having properties that exceed the specified strength and toughness requirements by a comfortable margin. Lai and Vilpponen (35) showed that the quality of procedure qualification tests is much better than the quality of production welds. In addition, they showed that automatic processes are less dependent on operator skill, and are less prone to procedural defects such as porosity and slag inclusions. The variation in quality of automatic processes is less than that of manual processes.

However, manual welding with stick electrodes (SMAW) is versatile and readily adaptable, especially for out-of-position welding. SMAW usually has smaller weld beads and a low deposition rate, resulting in a relatively low net heat input. Despite lower productivity, this can have advantages, because it results in a tough microstructure in the weld metal and a smaller brittle layer in the heat-affected zone. It also reduces liquation micro-cracking in the heat-affected zone.

GMAW would be expected to have fewer problems with hydrogen-assisted cracking in the weld metal, since it is considered to be the process with the least hydrogen potential (except for GTAW, which is not commonly used in shipyards for thick-section steel welding). GMAW appears to give the highest notch toughness because of the faster cooling time of the weld metal and inherently fewer inclusions produced during this process compared to the flux-shielded processes. However, SAW is easier to use in a shipyard environment because of the positive shielding provided by the flux. It is not subject to the effects of drafts and cross-winds, nor to nozzles plugged by spatter, with consequent loss of shielding, as can happen with gas- shielded processes.

The high deposition rate of SAW is attractive for reducing costs and can result in good weld-metal notch toughness if a high proportion of acicular ferrite is achieved in the weld metal. A high heat input can slow the cooling time, enabling a higher fraction of acicular ferrite to form in the weld metal. In addition, the weld metal deposits are usually high quality, with higher notch

toughness than SMAW. According to Braid and Gianetto (36), the reason for this is lower oxygen levels of the SAW deposits and consequently, a lower number of large (greater than 1 μ diam) non-metallic inclusions which act as cleavage crack initiation sites.

But, in conclusion, SMAW will not be readily displaced as the process used for much of the welding in shipyards, because of its inherent versatility. The only process which may offer an alternative for out-of-position welding is manual pulsed GMAW, which still requires some development work, especially for welding HY-100.

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Table 1 - Target values for HY-100 welding consumables, MIL-STD-23765/2C (SH). Target values for HY-80 consumables are shown for comparison.

Target values for weld metal			
		HY-80	HY-100
Yield Strength	MPa (ksi)	565-758 (82-110)	703-785 (102-114)
Charpy	J (ft. lbs)		
	18 C (0 F)	81 (60)	81 (60)
	-51 C (-60 F)	47 (35)	47 (35)
Dynamic Tear	J (ft. lbs)		
	-1 C (30 F)	610 (450)	610 (450)
	-29 C (-20 F)	407 (300)	407 (300)

Table 2. Comparison of deposition rates for various processes, welding HY-100 steels, as discussed in the report.

Process	Deposition Rate (kg/h)	Source
SMAW	1 - 2	Shackleton (1973)
GMAW - Conventional	2 - 4	Shackleton (1973)
Narrow gap	8 - 10	Laing et al (1985)
GTAW - Cold Wire	1 - 2	Shackleton (1973)
Hot wire	4 - 6	Flax et al (1971)
SAW - Single Wire	6 - 9	CANMET Grosse-Wordemann(1986)
Tandem	13	Grosse-Wordemann(1986)

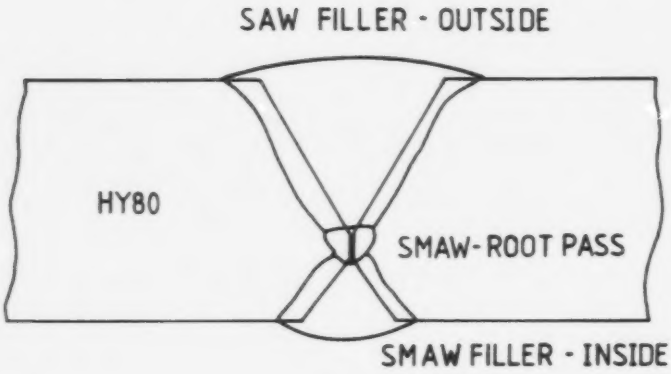


Fig. 1 - One U.K. procedure for submerged-arc welding of HY-80 submarine pressure hulls (after Ref. 3).

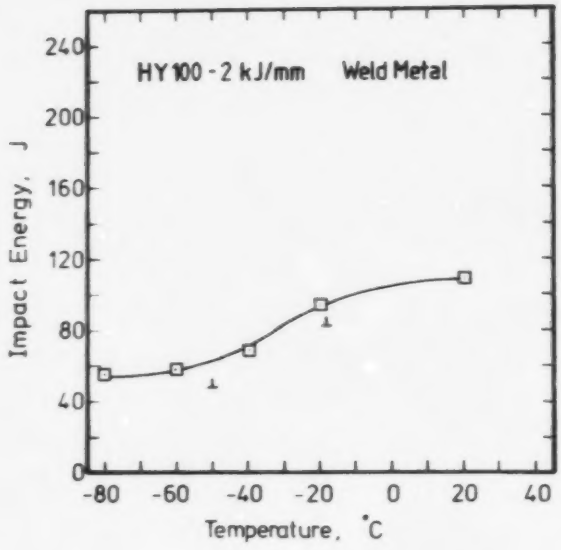


Fig. 2 - Charpy transition curves for HY-100 SAW weld metal specimens, after hydrogen removal treatment in furnace. Notch toughness target values are indicated by symbol +.

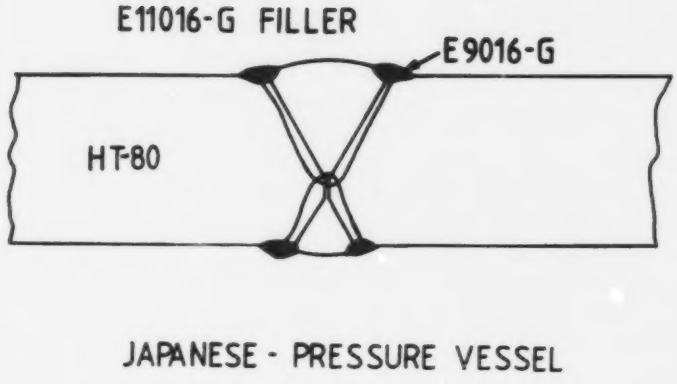


Fig. 3 - One Japanese procedure for welding high strength pressure vessel steels (after Ref. 22).

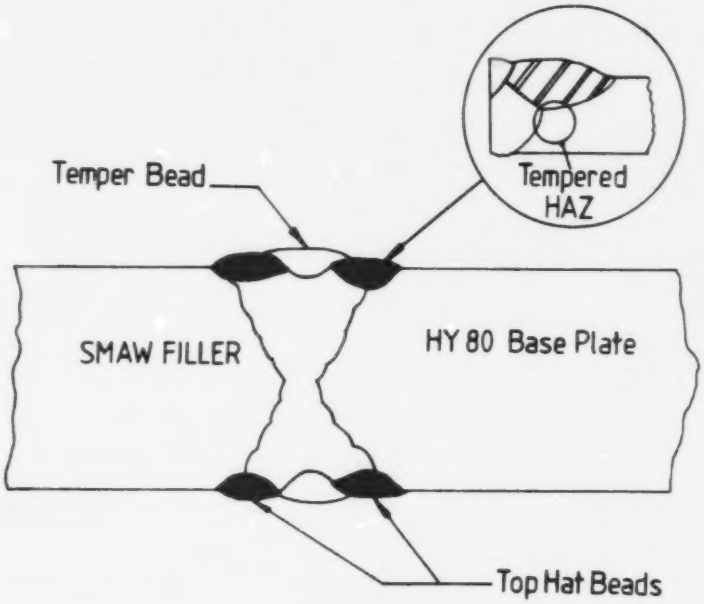


Fig. 4 - A schematic of the "Top hat" bead welding procedure in SMAW welding of HY-80. The two extreme capping passes are located about 8 mm beyond the edge of the joint preparation (after Ref. 23).

APPENDIX 1

Manufacturers known to be active in developing welding consumables for HY-100 steels.

Company	Contact	Phone No.
LTEC	John Makarchuk, Toronto	416-762-0220
	Kevin Lyttle, Ohio	216-992-1269
Kobe	Yogi Ogata, Houston	713-981-9290
Lincoln	Mike Vuchnich, Toronto	416-421-2600
	Dick Seif, Ohio	216-481-8100
Hobart	Dave Fink, Woodstock	519-537-6291
Oerlikon	Mike Hayes, Houston	713-466-0102
Trimark	Charles Ridenour, Ohio	513-773-2010
Canadian Liquidaire	Viwek Vaidya, Montreal	514-255-7741
Alloy Rod	Stan Ferree, Pennsylvania	717-637-8911
ESAB	Claude Lemieux, Toronto	416-671-2762
Thyssen	Roger Swain, Illinois	312-682-3900
Teledyne-Mackay	Damian Kotecki, Pennsylvania	717-845-7581

APPENDIX 2

PHYSICAL METALLURGY RESEARCH LABORATORIES
REPORT: PMRL 86-67(INT)

THE DEVELOPMENT OF WELDING PROCEDURES FOR THE JOINING OF HIGH STRENGTH HY100 STEEL

by

J.T. McGrath, J.A. Gianetto, R.F. Orr and D.E. Dolan

1. INTRODUCTION

High strength steels such as HY80 and HY100, used in the fabrication of submarine pressure hulls, present new challenges to welding fabricators. Welding procedures must be developed to prevent weld cracking and to produce metallurgically sound weld metals. In an initial program (1) on the welding of HY80 steel, welding consumables were selected and weld procedures developed that produced sound weld metals with mechanical properties (strength and notch toughness) that achieved the targeted values from current military standards (2).

There are some restrictions that may make the welding of HY100 more difficult. Although welding heat inputs up to 4 kJ/mm are acceptable according the the military standard STD-1688(SH) (2) for welding of HY80, a restriction of 2.2 kJ/mm (maximum) has been stipulated for the welding of HY100. In order to provide 100% joint efficiency, i.e., weld strength of 703 MPa, the use of low preheat and interpass temperatures in addition to a low energy input are required. Because of the high strength and hardenability of the HY100 steel and the corresponding weld deposits, there is a relatively high risk of delayed hydrogen cold cracking occurring in both the heat-affected zone and the weld metal.

The objective of the present program is to develop welding procedures that will produce metallurgically sound welds and achieve the required

mechanical properties in HY100 weldments deposited by the submerged arc welding process. This report summarizes the initial results of the welding procedure development program.

2. EXPERIMENTAL

2.1 WELD PREPARATION

Submerged-arc welds were made in 25 mm thick HY100 high-strength steel using 2.4 mm diam Linde 120 wire and Oerlikon OP121TT basic flux at 2, 3 and 4 kJ/mm heat inputs. The composition of the HY100 steel is listed in Table 1. The range of heat inputs was chosen to provide data for comparison with previous research on HY80 steel weldments.

A single-vee joint design consisting of a 60° included angle and a land of 6-10 mm was selected to accommodate the increasing heat inputs. Table 2 shows typical parameters used for the submerged-arc welds. The plates were preheated to 93°C and a maximum interpass temperature of 150°C was maintained. The submerged-arc flux was used directly from heated storage ovens held at 100°C. After completing the first side of the joint the plates were turned and carbon-arc backgouged to sound metal prior to depositing the final back passes. The pass sequences are shown in Fig. 1.

2.2 METALLOGRAPHIC EXAMINATION

Two sections, transverse and parallel to the welding direction, were cut from each weld as shown in Fig. 2. The samples were prepared using standard metallographic techniques. The weld metal and HAZ microstructures were characterized using a light optical microscope. Diamond pyramid microhardness transverses were made across the weld zones using a 500 g load.

2.3 NONDESTRUCTIVE TESTING

Gamma and X-ray radiography and magnetic particle nondestructive testing (NDT) methods were used to inspect the welds for defects or cracks.

3. RESULTS

3.1 WELD METAL STRUCTURE AND PROPERTIES

As shown in Fig. 3 and 4, the microstructure of the weld metal was composed primarily of fine acicular ferrite for the three heat inputs. Weld-metal cracking was observed in all welds. These cracks were transverse to the welding direction and located primarily in the central portion of the weld through-thickness. The cracks had a maximum length of approximately 30% of the thickness. As shown in Fig. 5, the cracks were most prominent in the welds deposited at 2 and 3 kJ/mm.

The hardnesses of the welds are listed in Table 3. There was no significant difference in hardness as a function of heat input. This reflects the fact that the weld microstructure did not change significantly with heat input.

3.2 HEAT-AFFECTED-ZONE STRUCTURE AND PROPERTIES

The coarse-grain heat-affected zone (CGHAZ) adjacent to the weld fusion line contained martensite for all welds prepared at the three heat inputs (Fig. 6). The high hardnesses listed in Table 3 coincide with the presence of martensite. Although no indications of cold cracking were found in the CGHAZ grain boundary, liquation cracking was observed sporadically as shown in Fig. 6. The tendency for liquation cracking was more prevalent in the weld prepared at 4 kJ/mm.

3.3 NDT EXAMINATION

Gamma radiography revealed weld cracks in the 2 kJ/mm and 3 kJ/mm welds only. Using X-ray radiography, additional indications of weld cracks were found in all three welds. The magnetic particle technique did not indicate surface cracks in the welds. However, magnetic particle inspection on welds sectioned along the centreline did reveal extensive cracking particularly in welds deposited at 2 and 3 kJ/mm.

4. DISCUSSION

Although the metallographic results indicate that the fine ferritic microstructure in HY100 welds deposited by submerged arc welding in the heat input range of 2 to 4 kJ/mm should provide both high strength and acceptable

notch toughness properties, the occurrence of weld metal transverse cracking must be eliminated. This cracking is a form of cold cracking which is dependent upon three main factors: (a) the presence of hydrogen, (b) a susceptible microstructure, and (c) a high residual stress field in the weld. Furthermore, the low preheat and interpass temperatures (93-150°C) increase the likelihood of developing cold cracks.

Work reported by Takahashi and Iwai (3) on transverse cracking in thick section 2.25 Cr-1 Mo steel submerged arc weld metals can provide some guidelines on solving the problem of weld cracking. They performed quantitative analyses of the residual stress pattern and hydrogen concentration profiles in a series of welds. Their data showed that the longitudinal residual stresses combined with a high concentration of diffusible hydrogen (5 cc/100 g) in the weld metal were the key factors responsible for the weld cracking. They recommended that the reduction of hydrogen in the weld metal should be the primary objective in reducing the tendency for the formation of transverse cracking in the weld metal.

Because the observations of transverse weld cracking in the Japanese study are very similar to the present observations of cracking in HY100 weld metal, future work will be directed at methods for reducing the level of hydrogen in the weld metal.

REFERENCES

1. J.T. McGrath, J.A. Gianetto, R.F. Orr and M.W. Letts, PMRL Report 86-50(J), 1986.

2. U.S. Dept. of Defence, Military Specification MIL-Std-1688(SH) 1981.

3. E. Takahaski, and K. Iwai, ASTM STP 755, p. 418 (1980).

Table 1 - Chemical composition of HY100 and SA weld metals

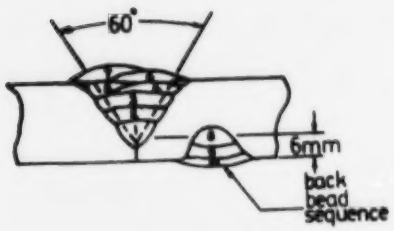
Weld No.	Element wt %												
	C	Mn	Si	S	P	Sn	Al	Cr	Mo	Ni	V	Ti	Nb
HY100	0.17	0.33	0.23	0.008	0.010	0.005	0.03	1.52	0.48	2.62	0.005	<0.005	0.02
SA22	0.08	1.12	0.39	0.006	0.014	0.005	0.02	0.71	0.50	2.20	0.010	0.005	0.02
SA32	0.08	1.15	0.39	0.006	0.014	0.005	0.02	0.71	0.50	2.20	0.010	0.005	0.02
SA42	0.08	1.12	0.38	0.006	0.014	0.005	0.02	0.72	0.50	2.20	0.010	0.005	0.02

Table 2 - Submerged-arc-welding parameters

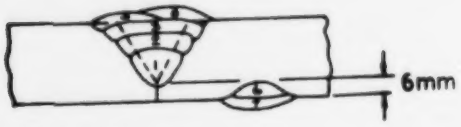
Weld No.	Pass No.	Current (A)	Voltage (V)	Wire feed speed (mm/s)	Travel speed (mm/s)	ESO (mm)
SA22	1-10	450	35	55.0	7.8	25
SA32	1-7	500	35	61.4	5.9	25
SA42	1-4	600	35	76.2	5.1	25

Table 3 - Microhardness of HY100 weldments

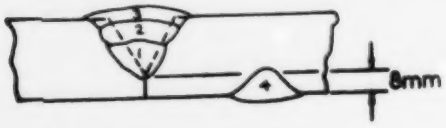
Weld No.	Microhardness, DPH	
	Weld metal	Coarse grain HAZ
SA22	293	435
SA32	286	405
SA42	294	384



(a) Weld SA 22



(b) Weld SA 32



(c) Weld SA 42

Fig. 1 Pass sequences of HY100 submerged arc welds (a) 2 kJ/mm (b) 3 kJ/mm and (3) 4 kJ/mm

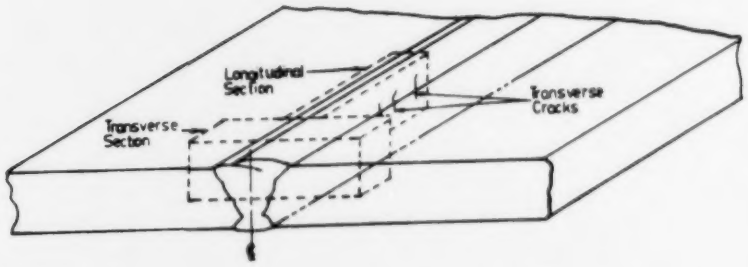


Fig. 2 Metallographic specimen location in submerged arc welds

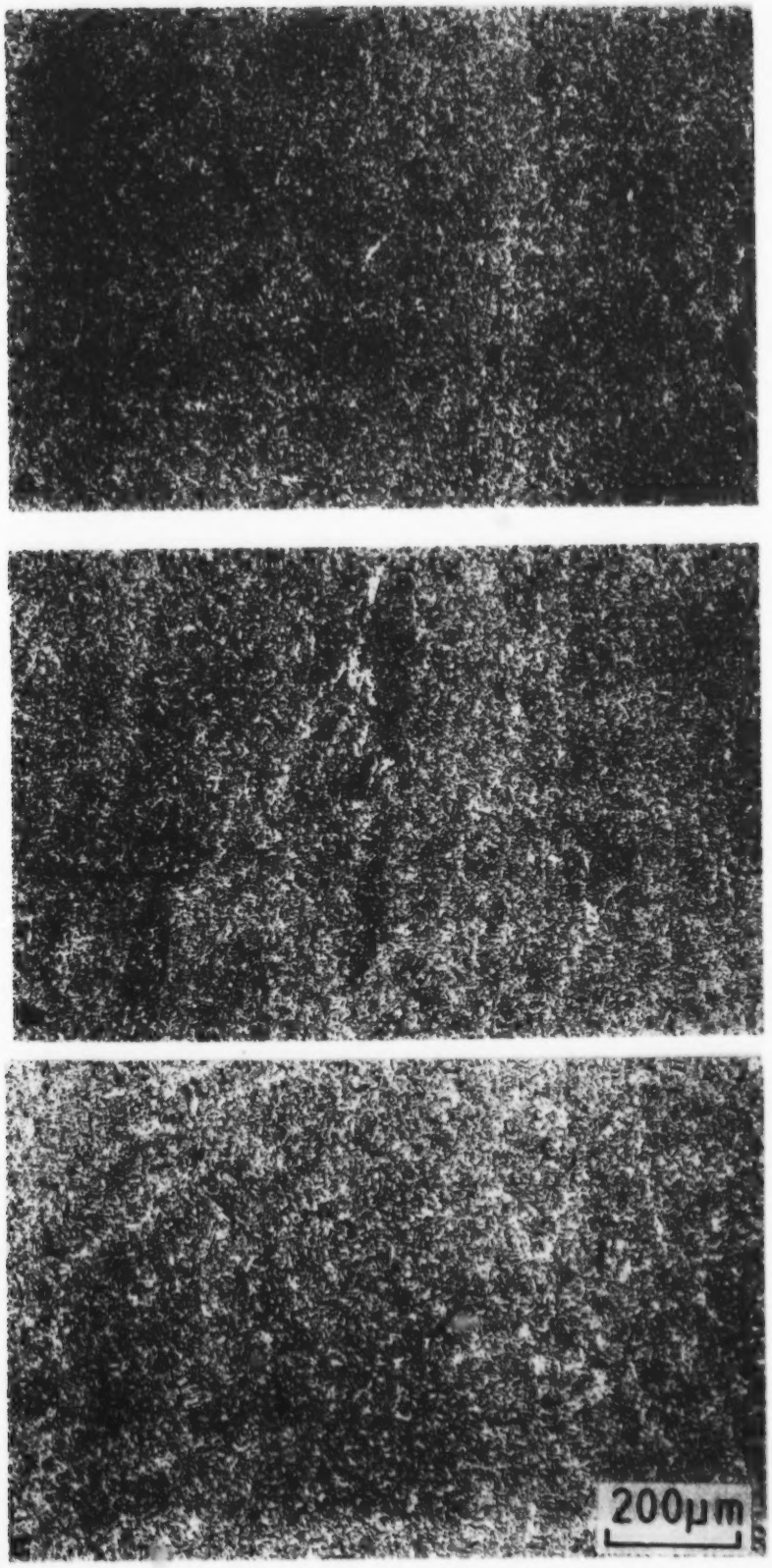


Fig. 3 Weld metal microstructure of SA welds deposited at (a) 2 kJ/mm (b) 3 kJ/mm and (c) 4 kJ/mm

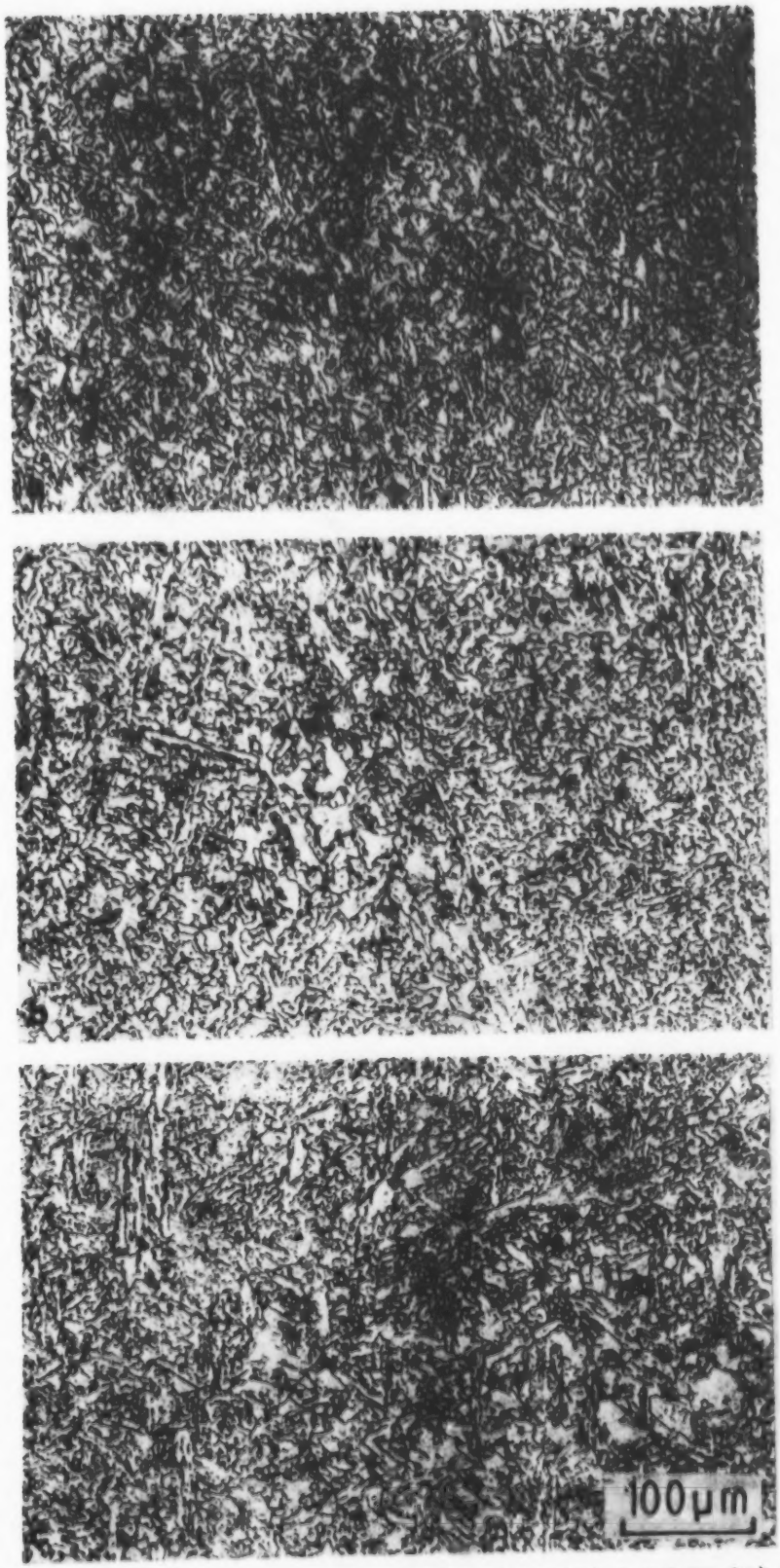


Fig. 4 Microstructural constituents of SA welds (a) 2 kJ/mm (b) 3 kJ/mm and (c) 4 kJ/mm

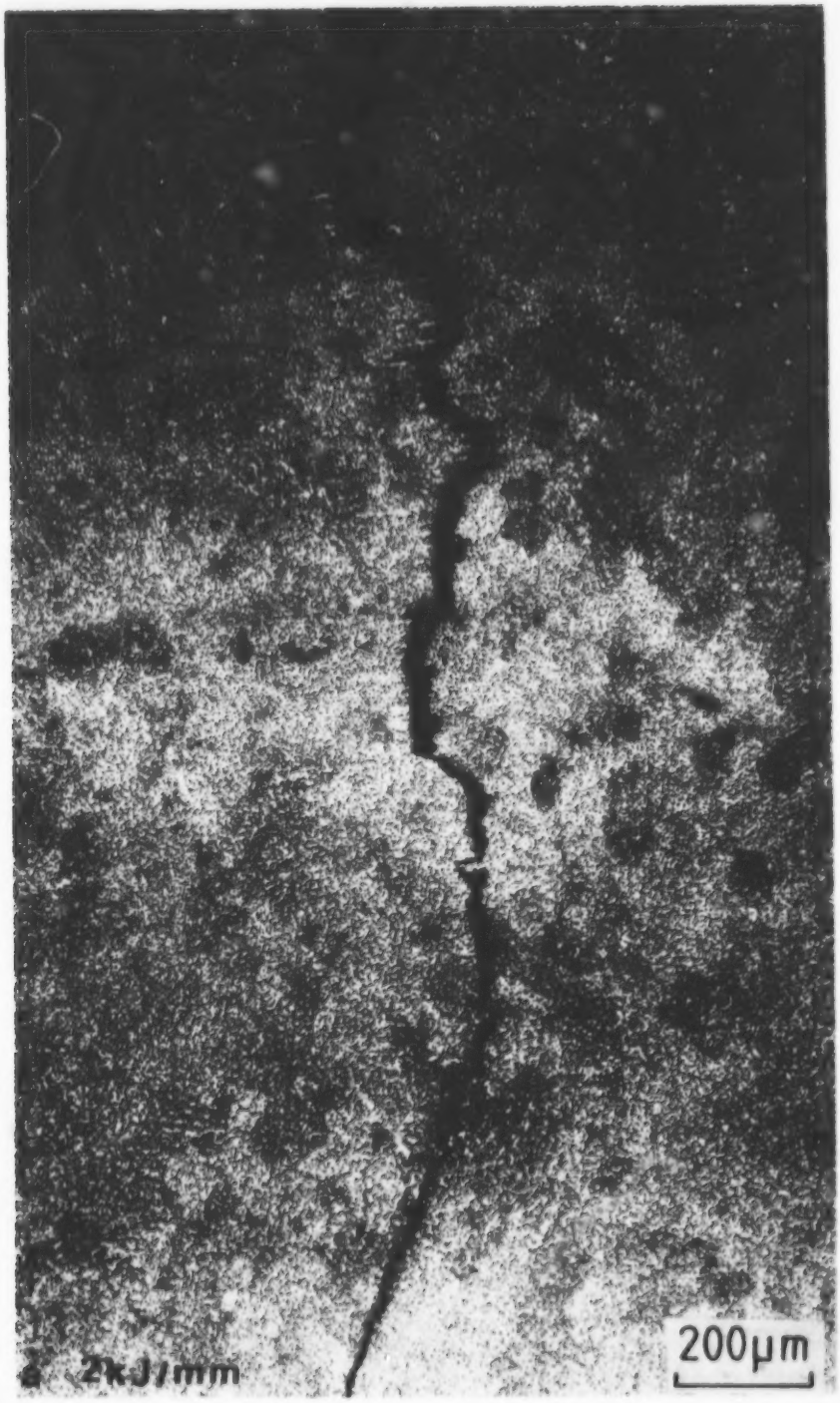


Fig. 5 Micrographs of transverse cold cracks in HY100 weld metals. Metallographic samples were taken from longitudinal sections as per Fig. 2.

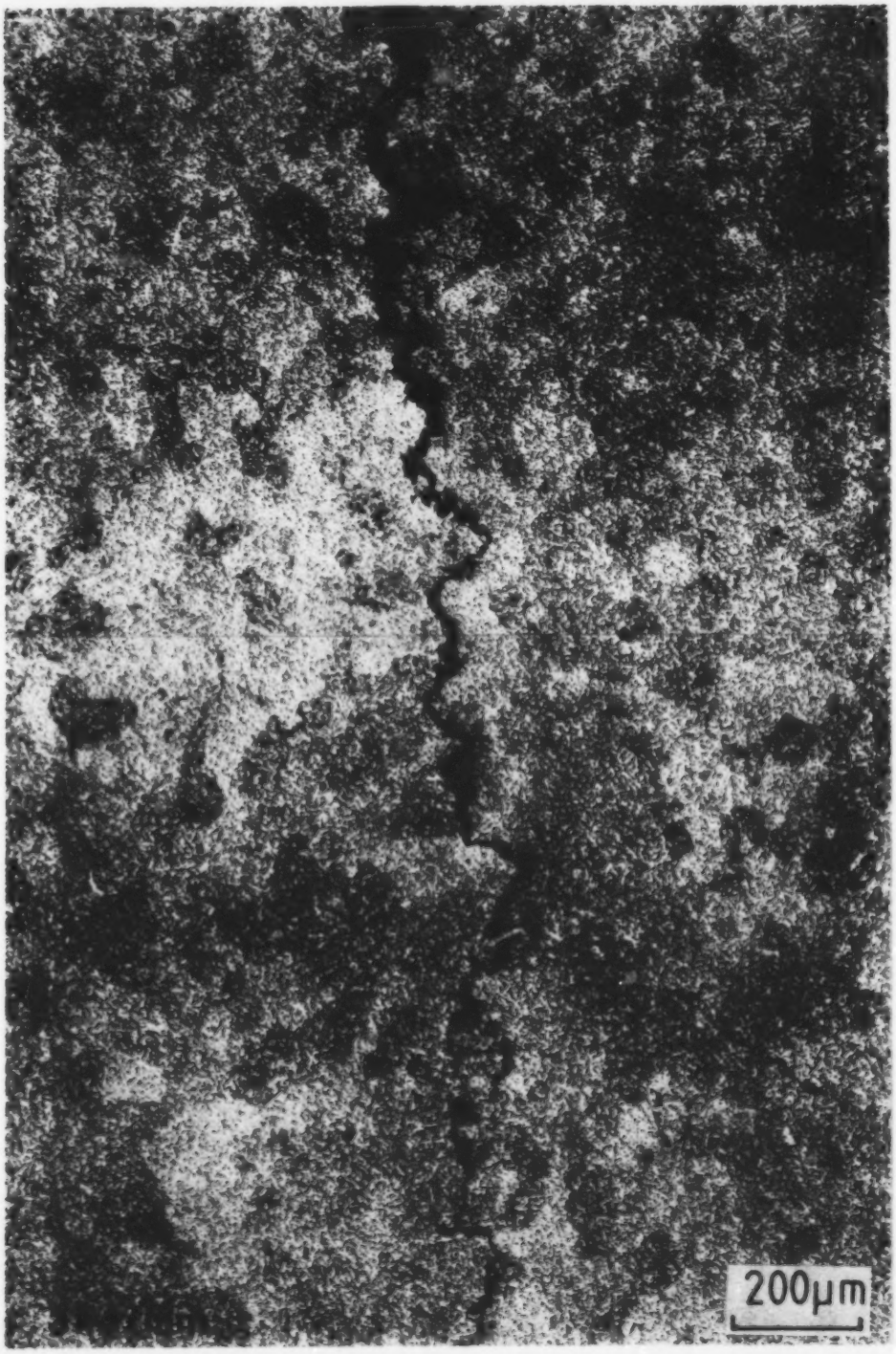


Fig. 5 cont'd

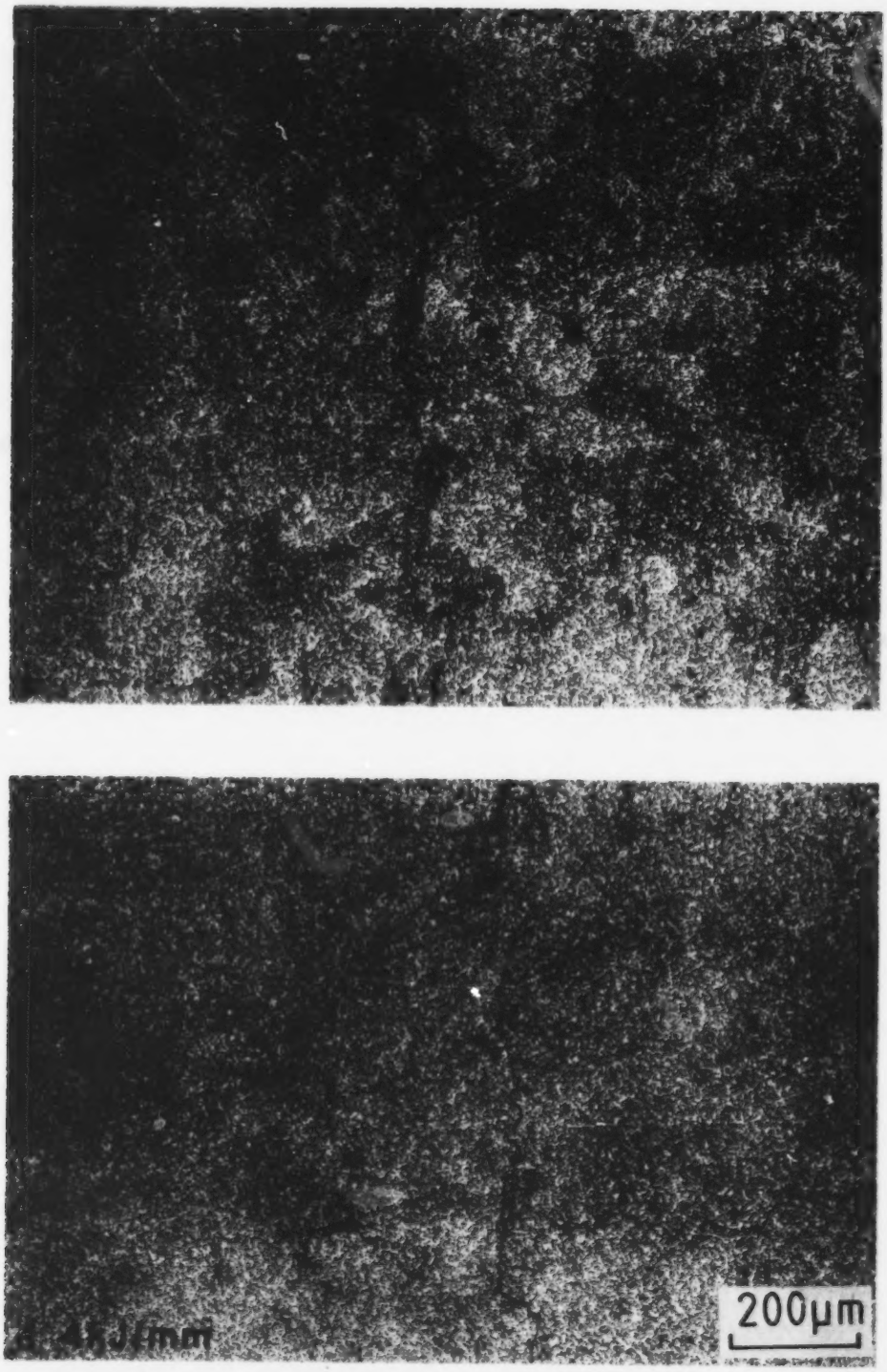
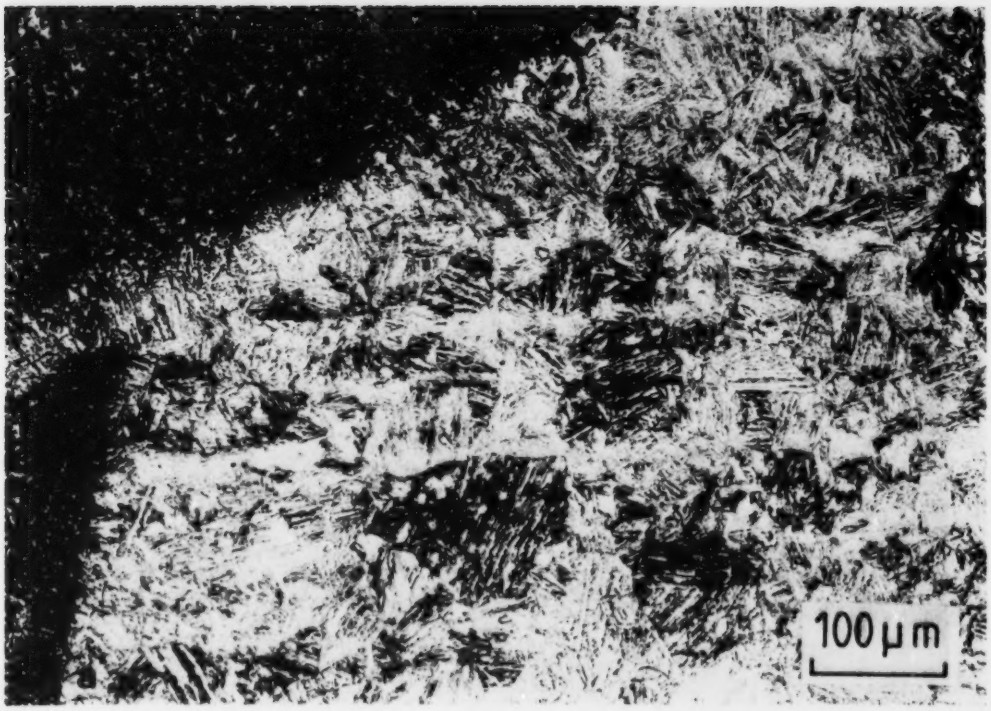


Fig. 5 cont'd



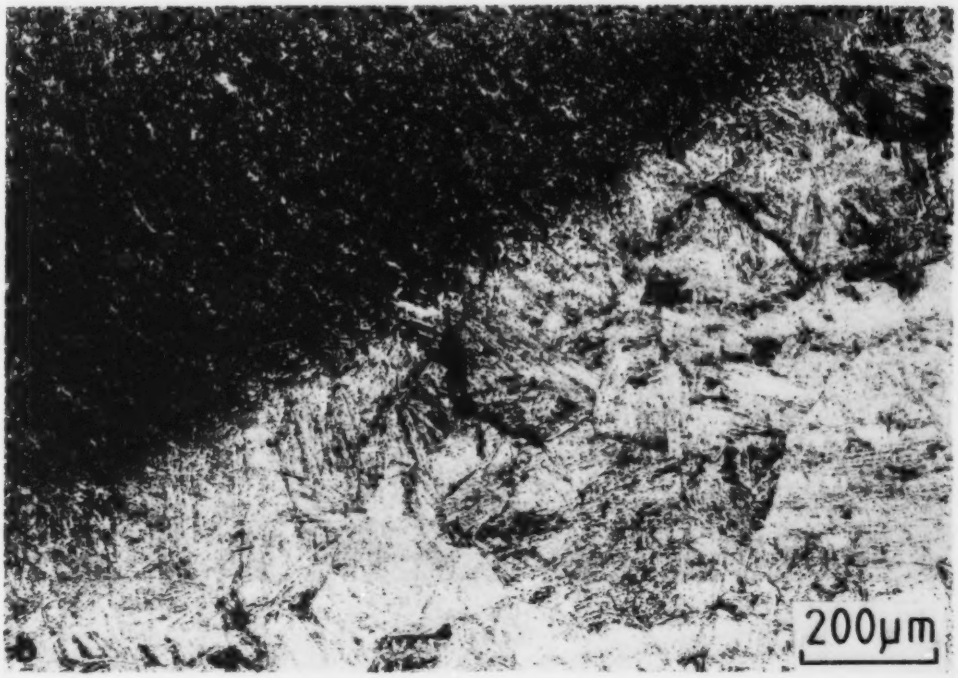


Fig. 6 Microstructure of CGHAZ adjacent to fusion line in HY100 welds deposited at (a) 2 kJ/mm and (b) 4 kJ/mm. Note liquation cracks in 4 kJ/mm weldment.